Development of Etalon-Type Gain-Flattening Filter

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ABSTRACT As a result of rapid increase of amount of traffic data and transmission rates in telecommunication, the wavelength division multiplexing (WDM) system has been studied. An erbium-doped fiber amplifier (EDFA) which is a key component in this system needs flat gain spectra. One of the gain-flattening technologies is usage of an optical gain-flattening filter that has a reverse loss profile against the gain profile of EDFA. We have developed a design method using nonlinear fitting upon an etalon-type gain-flattening filter, so we can design a gain-flattening filter that has less error against any gain spectra than conventional methods. Thereupon we have manufactured modules designed by the method, and we can get excellent performance upon gain-flattening filters. In this paper, we demonstrate the design method and report performances of several types of gain-flattening filters for optical amplifiers that have different gain spectra.

1. INTRODUCTION

As the Internet is spreading all over the world, telecommunication technologies to meet the rapid increase in traffic capacity and rate are urgently needed. Conventional means involves increasing the bit rate to expand traffic capacity. Recently WDM system using different wavelength optical signals that has been investigated for enlargement of traffic capacity has been reported year after year. One of the key devices supporting WDM system is EDFA, which amplifies light signals with stimulated emission by pumping erbium ion doped in optical fiber with pumping light. EDFA, which can amplify different signals spreading in a wide range, is needed as the amplifier of transmission in the system.

The gain spectrum of EDFA has asymmetrical twin peaks, due to a luminescent spectrum caused by fine structure of the energy levels. The gain spectrum isn't flat, so there is power deviation between amplified signals. In the long haul optical transmission systems, optical signals are transmitted by a multi-amplifier system, so differences between optical signal powers are accumulated. When dividing optical signals for various wavelengths at the receiver, other optical signals affect the signal as noise. If there are differences between optical signals transmitted by amplifiers, optical signals with low signal to noise ratio are more and more deteriorated at WDM as that are transmitted by EDFA. So the transmission distance becomes shorter and the wavelength range of transmittance and the number of signal channels decrease. Therefore, it is needed that the gain of EDFA be flat in the range of signals for getting an adequate signal to noise ratio at each wavelength. One of the methods to flatten gain of EDFA is using an optical gain-flattening filter. This is the method to flatten the gain of EDFA by using a filter with reverse loss spectrum against the gain spectrum. This filter is called the optical gain-flattening filter.

We established a method to design an optical gain-flattening filter with Fabry-Perot etalon by nonlinear fitting, so we can manufacture optical gain-flattening filters with loss profiles accommodating to various gain spectra. As the result of evaluation of sample modules, we confirmed that characteristics of these samples correspond to the design. And gain characteristics of EDFA with the optical gain-flattening filter is excellent. Moreover, we made sure that these filters are reliable as optical devices for telecommunication by reliability tests.

2. OPTICAL GAIN-FLATTENING FILTER

As the method of flattening a gain spectrum of EDFA, methods using optical gain-flattening filter with reverse loss spectrum against gain spectrum have been investigated. The principles of optical gain-flattening filter are shown in Figure 1. It is shown that EDFA has gain dependence on wavelength before flattening. After flattening of gain by using the optical gain-flattening filter, it is shown that dependence of EDFA on wavelength is flattened and deviation of signal power is improved. In Figure 2 sample configuration of EDFA with optical gain-flattening filter is shown. Normally optical gain-flattening filter is used in

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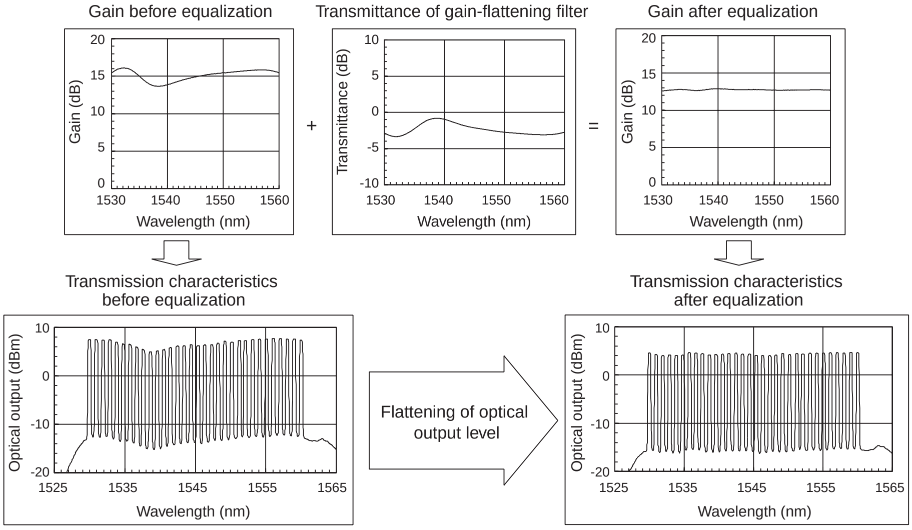

Figure 1 Function of optical gain-flattening filter

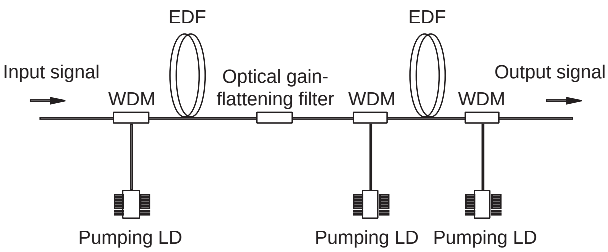

Figure 2 Configuration of a typical EDFA

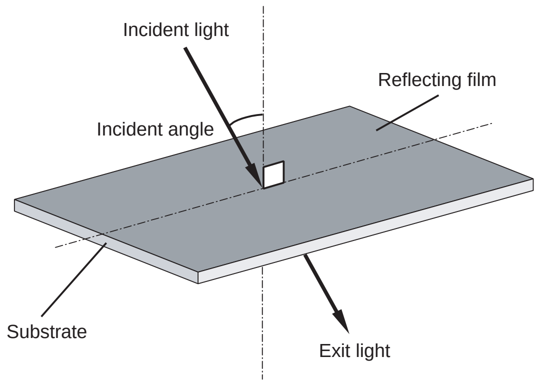

Figure 3 Schematic diagram of the Fabry-Perot etalon filter

series with EDFA as shown in Figure 2, where the filter is inserted in the middle stage of EDFA between two erbium doped fibers (EDFs).

The gain-flattening using passive components has been investigated. Optical filters such as an etalon filter [1)~3)], a dielectric filter [4)], and a long period fiber Bragg grating filter [5)], a Mach-Zehnder type filter [6)], and the split-beam Fourier filter [7)] are proposed. The above-mentioned intrinsic EDFA gain-wavelength characteristics have asymmetrical twin peaks and the loss-wavelength characteristics of the optical gain-flattening filter to compensate the EDFA gain-wavelength characteristics have counterbalanced characteristics. The EDFA gain-wavelength characteristics depend on power characteristics of pumping lasers, the concentration of erbium ion in EDF, the kind of co-doped ion and its volume, and the length of EDF as well.

The gain-flattening filter requires flexibility of design for various kinds of EDFA gain-wavelength characteristics to minimize errors between the target and design. Moreover it is required to have low polarization dependence loss (PDL) and capability of producing highly reproducible spectral profiles.

3. ETALON-TYPE GAIN-FLATTENING FILTER

The intrinsic EDFA gain-wavelength characteristics have asymmetrical twin peaks and the required loss-wavelength characteristics of an optical gain-flattening filter to compensate the EDFA gain-wavelength characteristics depend on the signal wavelength bandwidth and the required gain of EDFA. We can design optical gain-flattening filters using several kinds of etalon filters. In this section characteristics of Fabry-Perot etalon filter used in the etalon-type gain-flattening filter and the design are described.

3.1 Characteristics of Etalon Filter

The Fabry-Perot etalon filter named after its inventors can be considered as archetype of the optical resonator and it is a one-dimensional resonator. It uses interference phenomena of multiple reflections between mirrors paralleled in medium. Figure 3 shows the etalon filter that we use in the gain-flattening filter. It is produced by grinding two plane-parallel faces on a substrate with thickness d and index n and then evaporating a dielectric layer of

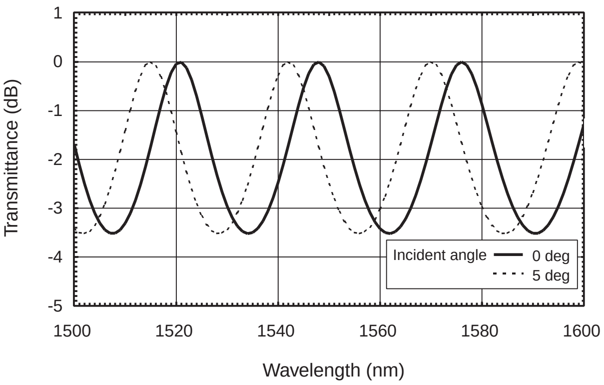

Figure 4 Characteristics of a Fabry-Perot etalon filter

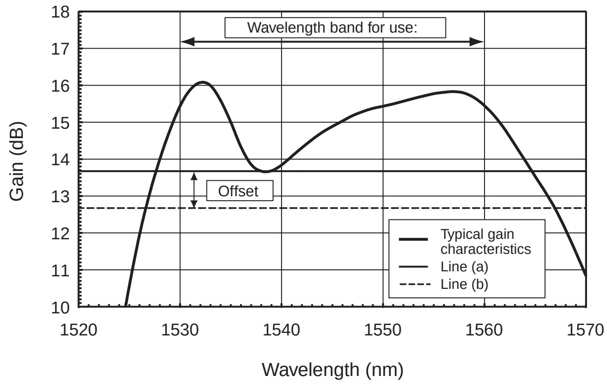

Figure 6 Typical gain spectrum of the EDFA

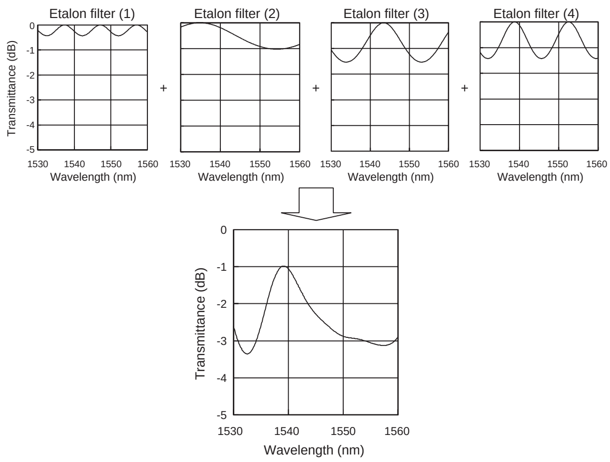

Figure 5 Principles of the etalon-type gain-flattening filter

reflectance *R* on the surface.

Taking the case of incidence angle θ, we obtain the following expression of transmission characteristics of the etalon filter in air [8]:

$$T(\lambda)=10\log\left[\frac{(1-R)^2}{(1-R)^2+4R\sin^2(\delta/2)}\right] \tag{1}$$

where δ is the phase delay given by

$$\delta=\frac{4\pi nd\sqrt{1-\sin^2\theta/n^2}}{\lambda}$$

Figure 4 shows the sample characteristics of an etalon filter. It has periodic characteristics similar to a sine wave. We can obtain any amplitude of transmission characteristics by optimizing reflectance *R* and any phase by optimizing thickness *d*. As shown in Figure 4 by changing the incidence angle θ we can control the phase.

3.2 Principles of Etalon-type Gain-flattening Filter

The etalon-type gain-flattening filter consists of several etalon filters with different amplitudes and phases to compensate asymmetric EDFA gain-wavelength characteristics for flattening gain shapes. Figure 5 shows the principles of the etalon-type gain-flattening filter. In this case it is shown that by using four etalon filters with different amplitudes and phases the loss-wavelength compensating EDFA gain characteristics is obtained. The fine control of thickness and reflectance of each etalon filter is needed to obtain each amplitude and phase of etalon filters.

3.3 Design of Etalon-type Gain-flattening Filter

Figure 6 shows sample gain-wavelength characteristics of EDFA. In this case the signal wavelength bandwidth is from 1530 nm to 1560 nm. We can obtain flat gain characteristics in the bandwidth by compensating gain-wavelength characteristics over the basis of line (a) that shows minimum gain in this area or line (b) that shows a gain less than minimum. The design of the gain-flattening filter depends on deciding the basis of gain and it is one of parameters of the design. There is a difference between the minimum gain level and the basis level used in the design, which is named difference offset. In the design process, the number of etalon filters composing gain-flattening filter and thickness and phase of each etalon filter, in other words reflectance and thickness of etalon filters and incident angle, are acquired.

Design methods of etalon-type gain-flattening filter such as methods based on the loss peak [3] and Fourier series expansion [2] are proposed. We established a method using nonlinear fitting. For instance, transmittance of etalon-type gain-flattening filter composed of m sheets of etalon filters is expressed by

$$T(\lambda)=\sum_{j=1}^{m}10\log\left[\frac{(1-R_j)^2}{(1-R_j)^2+4R_j\sin^2(\delta_j/2)}\right] \tag{2}$$

where δ_j is phase delay of each etalon filter,

$$\delta_j=\frac{4\pi nd_j\sqrt{1-\sin^2\theta_j/n^2}}{\lambda}$$

Our design method is looking for the number of etalon filters and characteristics of each etalon filer, amplitude and phase, in other words reflectance and thickness, by using nonlinear fitting method to minimize the least-square between target loss-wavelength characteristics and $T(\lambda)$. By using this method we can design an etalon-type gain-flattening filter with superior characteristics for flattening EDFA gain-wavelength characteristics.

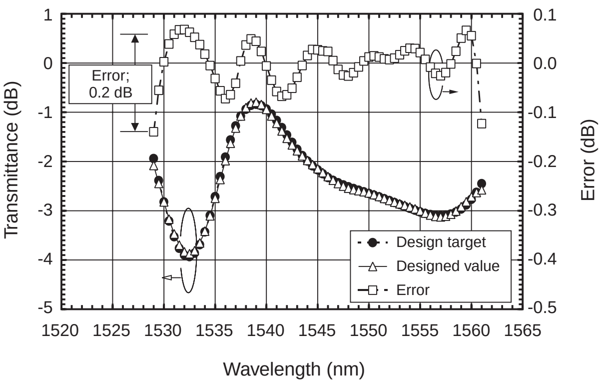

Figure 7 Designed characteristics of the etalon-type gain-flattening filter (1)

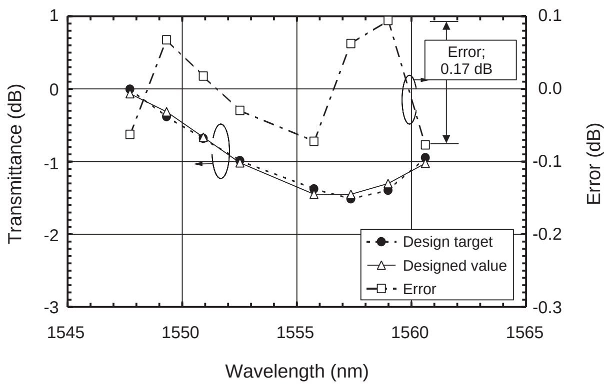

Figure 9 Designed characteristics of the etalon type gain-flattening filter (2)

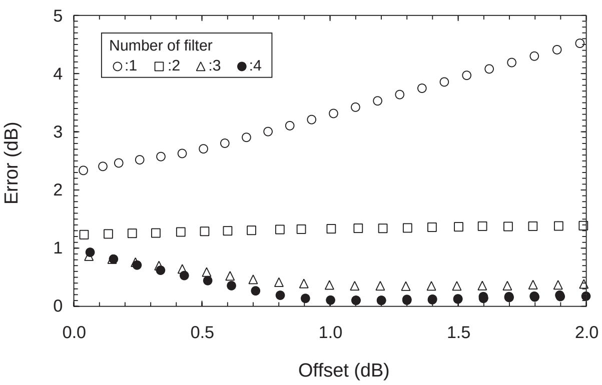

Figure 8 Dependence of error deviation on the number of etalon filters and offset for the etalon type gain-flattening filter (1)

Figure 10 Appearance of etalon-type gain-flattening filter

Figure 7 shows a sample design of an etalon-type gain-flattening filter with four etalon filters. In this figure, the target profile is loss-wavelength characteristics with offset. In this case, offset is 0.8 dB, and the error deviation between target and design characteristics is 0.2 dB. The error deviation mainly depends on the number of etalon filters and the offset. Figure 8 shows the relationship between offset and error deviation with the number of etalon filters as parameter. In this figure, using nonlinear fitting method with fixed offset we can get the error deviations. The error deviation is less when the offset and the number of etalon filters are increased. In this case, minimum error deviation is 0.1 dB with the four etalon filters and an offset of 1.2 dB. Increasing the offset, however, is increasing of the insertion loss of optical gain-flattening filter and decreasing the gain of EDFA. The relationship between offset and error deviation is the trade-off, and it is not guaranteed that the offset with least error deviation is optimum for EDFA. In the case of Figure 6, design with an offset of 0.8 dB is used for the above-mentioned reason.

The above-mentioned offset and number of etalon filters depend on target characteristics of the gain-flattening filter. Figure 9 shows another sample design of etalon-type gain-flattening filter with one etalon filter. In this case, the same as the above-named design shown in Figure 8, the design is suitable for EDFA use by the relationship between error deviations and offset as the parameter of the number of etalon filters. Design with an offset of 0 dB and an error deviation of 0.17 dB is used.

As mentioned above, target characteristics of an optical gain-flattening filter depend on the EDFA that employ the filter, since the gain characteristics of EDFA depend on the characteristics of optical components and configurations, such as EDF, pumping lasers, and other optical passive components. We develop the design method of etalon-type gain-flattening filter suitable for EDFA by using nonlinear fitting, so the gain-flattening filter has best configuration and characteristics of etalon filters. By this method we can design the optical gain-flattening filter for any type of EDFA.

4. EXPERIMENT

4.1 Configurations and Appearance

Figure 10 shows an experimental etalon-type gain-flattening filter. Its dimensions are 48 mm x ϕ 5.5 mm including the sleeve of the optical fiber. It is composed of non-spherical lenses for collimating optical beam and etalon filters between input and output lenses.

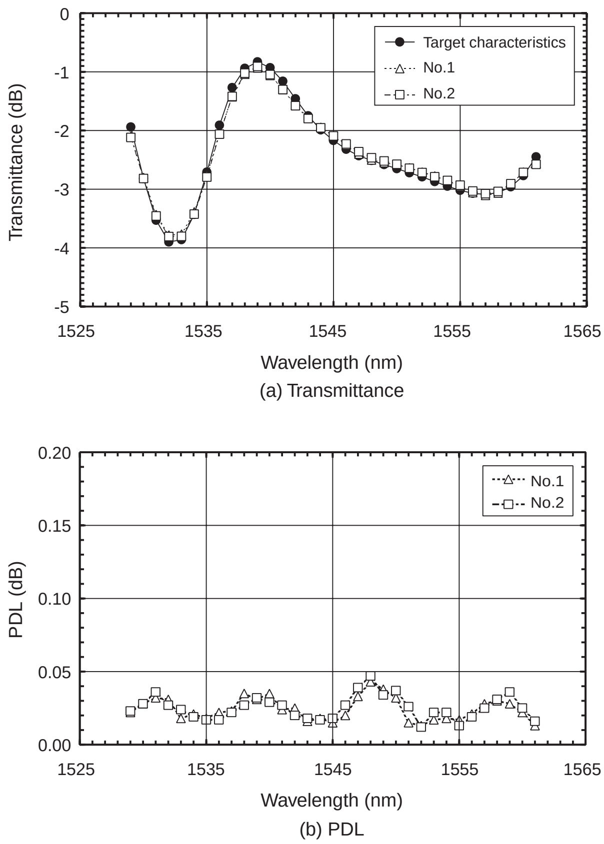

Figure 11 Characteristics of prototype gain-flattening filter of the etalon type (1)

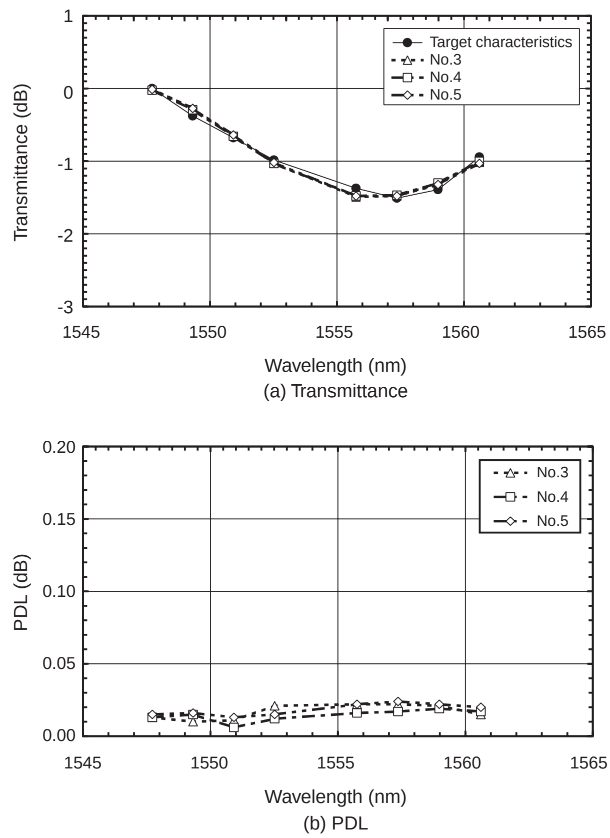

Figure 12 Characteristics of prototype gain-flattening filter of the etalon type (2)

4.2 Attachment of Etalon Filters into the Optical Path

In order to realize amplitude and phase of each designed etalon filter, it is necessary to control the thickness and reflectance of each, but there are practical errors. Especially accuracy of thickness that determines the phase of the filter is needed, but the real thickness does not fit the designed thickness because of the limit of manufacture. Tuning the insertion angle of etalon filters is needed to cancel the error of phase caused by the thickness error. So we developed a method optimizing the combination of the insertion angle of etalon filters for minimum error deviation by using nonlinear fitting with characteristics of etalon filters put to use, so the etalon-type gain-flattening filter becomes highly reproducible.

Problem of return loss and multi-reflection between etalon filters is eliminated by attention to the designed insertion angle of etalon filters and considering the optimized insertion angle during the attachment process.

Table 1 Results of reliability tests

Test item	Conditions	Results	
		Insertion loss change (dB)	Error deviation (dB)
Damp	85°C, 85%RH 336 hours	Avg: 0.06 Worst: 0.09	Avg: 0.08 Worst: 0.09
Vibration	10~55 Hz, 1.52 $mm_{p\text{-}p}$ 3 axes 2 hours/axis	Avg: 0.06 Worst: 0.07	Avg: 0.02 Worst: 0.06
Impact	1.8 $m_{p\text{-}p}$, 3 axes, 8 cycle	Avg: 0.10 Worst: 0.13	Avg: -0.08 Worst: -0.10
Low temperature	-40°C 336 hours	0.04	0.05
Heat cycle	21~76°C 42 cycles/2 weeks, 10~80%RH	Avg: 0.09 Worst: 0.14	Avg: 0.01 Worst: 0.05

4.3 Results

Figure 11 and Figure 12 show experimental results based on designs shown in Figure 7 and Figure 9. In each figure, (a) shows transmittances of composed etalon filters and (b) shows polarization dependence losses (PDL). Practical loss-wavelength characteristics of the gain-flattening filter include these losses and losses caused by optical collimating components. In the case of Figure 11, the average of error deviation between loss characteristics shown in (a) and target is 0.27 dB, and in the case of Figure 12, the average of error deviation between loss characteristics shown in (a) and target is 0.2 dB. Each PDL shown in (b) is low, and it is sure that each back reflection is over 45 dB.

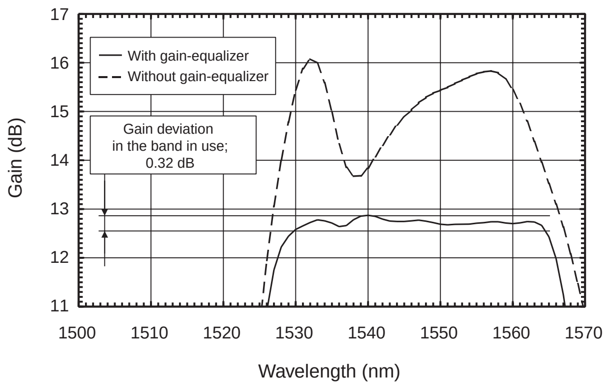

Figure 13 Gain spectrum of the EDFA with etalon-type gain-flattening filter

5. RELIABILITY TEST

In order to make sure of the reliability of the gain-flattening filter for optical passive components, reliability tests such as damp test, vibration test, impact test, low temperature test, and heat cycle test were carried out. Table 1 shows results of reliability tests. In every test, changes of error are less than 0.2 dB, so it is confirmed that etalon-type gain-flattening filter performs satisfactorily.

6. EDFA CHARACTERISTICS WITH ETALON-TYPE GAIN-FLATTENING FILTER

Figure 13 shows characteristics of EDFA with etalon-type gain-flattening filter. In the signal wavelength bandwidth from 1530 nm to 1560 nm, the gain deviation is 0.32 dB; and this flatness extends to 1565 nm, thus realizing an excellent flatness in gain characteristics.

7. CONCLUSION

We established the design method of etalon-type gain-flattening filter by using nonlinear fitting and analyzed the relationship between the number of etalon filters and offset for compensating any type of EDFA gain-wavelength characteristics and made it possible to design thickness and reflectance of etalon filters. It is possible to minimize error deviation caused in the assembly process by adjusting the insertion angle of etalon filters to cancel fabrication errors, thus we demonstrated the etalon-type gain-flattening filter is easy to fabricate and is capable of producing highly reproducible profiles suitable for any type of EDFA. Its PDL and back reflection are low for practical use. We also demonstrated EDFA with flat gain characteristics over a wide bandwidth by using the etalon-type gain-flattening filter. We have confirmed that this filter is reliable for optical passive components in telecommunications.

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